Environmental footprint of cooking fuels: a life cycle assessment of ten fuel sources used in Indian households

Punam Singh · Haripriya Gundimeda · Matthias Stucki

Abstract

Purpose Cooking energy is an essential requirement of any human dwelling. With the recent upsurge in petroleum prices coupled with intrinsic volatility of international oil markets, it is fast turning into a politico-socio-economic dilemma for countries like India to sustain future subsidies on liquefied petroleum gas (LPG) and kerosene. The aim of this paper is to evaluate and compare the environmental performance of various cooking fuel options, namely LPG (NG), LPG (CO), kerosene, coal, electricity, firewood, crop residue, dung cake, charcoal, and biogas, in the Indian context. The purpose of this study is to find environmentally suitable alternatives to LPG and kerosene for rural and urban areas of the country.

Methods The study assessed the cooking fuel performance on 13 ReCiPe environmental impact categories using the life cycle assessment methodology. The study modeled the system boundary for each fuel based on the Indian scenario and prepared a detailed life cycle inventory for each cooking fuel taking 1 GJ of heat energy transferred to cooking pot as the functional unit.

Results and discussion The cooking fuels with the lowest life cycle environmental impacts are biogas followed by LPG, kerosene, and charcoal. The environmental impacts of using LPG are about 15 to 18 % lower than kerosene for most environmental impact categories. LPG derived from natural gas has about 20 to 30 % lower environmental impact than LPG derived from crude oil. Coal and dung cake have the highest environmental impacts because of significant contributions to climate change and particulate formation, respectively. Charcoal produced from renewable wood supply performs better than kerosene on most impact categories except photochemical oxidation, where its contribution is 19 times higher than kerosene.

Conclusions Biogas and charcoal can be viewed as potentially sustainable cooking fuel options in the Indian context because of their environmental benefits and other associated co-benefits such as land farming, local employment opportunities, and skill development. The study concluded that kerosene, biogas, and charcoal for rural areas and LPG, kerosene, and biogas for urban areas have the lower environmental footprint among the chosen household cooking fuels in the study.

Keywords Cooking fuels · Dung cake · Environmental footprint · Household biogas · LCA · ReCiPe impact categories

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1 Introduction

Residential cooking constitutes the largest end use of energy (TEDDY 2010) in the Indian economy, and this study focuses on the environmental burden associated with the use of cooking fuels from a life cycle perspective. For systematic comparison of environmental performance, we included all possible fuel options to carry out the life cycle assessment (LCA). The recent national surveys (NSSO 2012; Census India 2011) show that the primary fuel used in rural areas were firewood (62.5 %), crop residues (12.3 %), liquefied petroleum gas, i.e., LPG (11.4 %), and dung cake (10.9 %), whereas in urban areas, LPG (65 %), firewood (20.1 %),

kerosene (7.5 %), and coal (2.9 %) were used for household cooking. During the last decade, there has been a noticeable increase in LPG use, particularly in rural areas, and use of kerosene has sharply declined in both rural and urban areas. Most coal is used for cooking in coal producing areas of the country. Overall, rural areas, where two-third population of the country lives, largely depend upon traditional biomass fuels, and most urban households fulfill their cooking energy needs from petroleum-based fuel sources.

The combustion of traditional fuels has long been associated with local environmental impacts, particularly indoor air pollution due to significant emissions of aerosols, methane, and nitrous oxide. LPG and kerosene, though, are relatively "clean fuels" but emit considerable carbon dioxide and other air pollutants during combustion in cook stove. Furthermore, the release of toxic chemical pollutants during the production of the fossil fuels causes environmental pollution of land, air, and water which adversely and irreversibly impacts the environmental quality. Also, according to Ministry of Petroleum and Natural Gas, India's dependence on oil imports have steadily increased (81.3 % import share) and accounted for about 6.3 % of its GDP in 2011. In the recent years, the import prices of crude oil have been highly volatile and rose steeply by 53 % from 2005 to 2011. To protect the household consumers from this extreme volatility in petroleum prices, the Indian government has been subsidizing kerosene and LPG. The public sector oil marketing companies usually bear most of the fuel subsidies on LPG and kerosene, which for instance amounted to about 442 billion rupees (9.7 billion USD) in 2011. Therefore, balancing the environmental footprint from large-scale use of traditional fuels and the economic burden imposed by petroleum-based fuel subsidy is an imposing and immediate challenge in front of the policymakers and stakeholders in India.

Earlier studies such as Balakrishnan et al. (2004), Bhattacharya et al. (2000), Kadian et al. (2007), Saud et al. (2012), Smith et al. (2000), etc. have examined the environmental performance of various cooking fuels. These studies exclusively focus on the combustion process of fuels in the cook stoves. Jungbluth (1996) carried out a restricted life cycle assessment of LPG and kerosene, and we used some of his findings as a benchmark for this study. Banerjee and Tierney (2011) compared household energy systems using life cycle exergo-environmental methods such as waste exergy, thermo-ecological cost, extended thermo-economic, etc. Other studies (Afrane and Ntiamoah 2011) have investigated the use of charcoal, LPG, and biogas for cooking in Ghana. On the whole, it can be said that environmental performance of cooking fuels over its entire life cycle has not been sufficiently addressed in the Indian context. The comprehensive scope of LCA is useful to evaluate the performance of the cooking fuels to avoid problem shifting, from one phase of the life cycle to another, from one region to another, or from one environmental problem to another (Finnveden et al. 2009).

The goal of this study is to determine the life cycle environmental impact of using firewood, crop residue, dung cake, charcoal, coal, electricity, LPG, kerosene, and biogas for cooking purposes. Both crude oil and natural gas are used to produce LPG and have a different production process, and hence, we treated the two categories separately in this study as LPG (CO), derived from crude oil, and LPG (NG), derived from natural gas. For evaluating the performance of the cooking fuels we considered 13 ReCiPe environmental impact categories, namely: (1) climate change (CC), (2) ozone depletion (OD), (3) human toxicity (HT), (4) photochemical oxidant formation (PCOD), (5) particulate matter (PM) formation, (6) terrestrial acidification (TA), (7) freshwater eutrophication (FWEP), (8) marine eutrophication (MEP), (9) terrestrial ecotoxicity (TET), (10) fresh water ecotoxicity (FWET), (11) marine ecotoxicity (MET), (12) fossil fuel depletion (FD), and (13) metal depletion (MD).

2 Methods

2.1 LCA methodology

We used the standard life cycle assessment guidelines developed by the International Organisation for Standardisation in its ISO 14040–14044 series to carry out this study. We used "SimaPro v.7.3.3" (PRe Consultants 2012) LCA software with embedded background "ecoinvent v2.2 database" (Ecoinvent Centre 2010) to evaluate the potential environmental impacts of cooking fuels. The basic structure of impact assessment methods in SimaPro is (a) characterization, (b) damage assessment, (c) normalization, and (d) weighting. The last three steps are optional according to the ISO standards and have not been used in this study.

2.2 Functional units

The energy required to cook one dish depends not only on the type and energy content of the fuel but also on the thermal efficiency of the cook stove used. There has been noticeable progress in stove designs towards improving its heat transfer efficiencies in recent years, particularly for biomass fuelled cook stoves. However, the dissemination of this cook stove to households has been largely on an experimental basis in few selected districts of India. The study considers the cook stove efficiencies (refer last column of Table 1) based on stove types most commonly used by Indian households (Venkataraman et al. 2010). We used "1 giga joules (GJ) of useful cooking heat" as the functional unit, which is defined as "net heat energy to the cooking pot after combustion of fuel in the cook stove." The household consumption of annual net cooking heat energy is the basis for the selection of "GJ" as units, which varied from 2 to 5.5 GJ among various rural and urban Indian population (NSSO 2012).

Table 1 Elemental composition of the cooking fuels

Fuel type	M %wt	C %wt	N %wt	O[a] %wt	H %wt	S %wt	Ash %wt	NCV MJ/kg	Stove[b] eff. (%)
Crop residues	14	42.1	0.36	48.37	6.3	0.17	2.7	12.84[c]	11
Firewood	22.4	46	0.30	44.87	5.8	0.01	3.02	13.95[c]	13.5
Dung cake	15.5	33.19	1.11	22.02	4.2	0.09	39.39	11.90[c]	8.5
Charcoal	1.7	80	0.74	10	1.8	0.06	7.4	27.41[c]	17.5
Coal	10	39	1.5	15	4	0.5	40	11.76[d]	15.5
Kerosene	0	85.9	0.05	0.05	13.8	0.2	0	42.86[d]	47
LPG	0	82.29	0	0	17.7	0.01	0	45.24[d]	57
Biogas	0	56.5	3.47	27.86	11.9	0.27	0	18.2	55
Comp. (in % vol)	CH$_4$, 60 %; CO$_2$, 34.5 %; N$_2$, 5 %; O$_2$, 0.32 %; and H$_2$S, 0.18 %								
Electricity (2008 prod. mix)	Coal, 65 %; hydro, 14 %; natural gas, 10 %; petroleum products, 4 %; nuclear, 2 %; and others, 5 %							3.6	70

[a] Oxygen content by difference

[b] Smith et al. (2000), Venkataraman and Rao (2001), Zhi et al. (2008), IS: 1342–1986, ISI 1984/06

[c] Calculated theoretical lower heating value

[d] National standards, e.g., IS: 1459–1974, IS: 4576–1978, National GHG Inventory (INCCA 2010), etc.

2.3 System boundary

The system boundary defines the input–output flow of process and material from "cradle to grave" of the selected fuel resources considered in the scope of the LCA. Figure 1a, b shows the simplified system boundary of biomass and fossil fuels commonly used by Indian households for cooking activities, respectively. The italics in the bold boxes show the processes that actively contribute to the release of pollutants. We have excluded infrastructure from the scope of LCA due to the lack of reliable data on the infrastructural requirements for the production of commercial fuels (LPG and kerosene) in India. This is also to ensure the consistency of the system boundary among the selected cooking fuels. Hence, the end of life infrastructural dismantling and disposal has also been omitted from the scope of LCA. Also, production of LPG and kerosene consists of several complex upstream and downstream processes which cannot be accommodated in this generic assessment; therefore, we included only the main production processes in the scope of this study. We also excluded the cook stove and its manufacturing to maintain consistency of the system boundary among cooking fuels, as mostly biomass fuels (including coal and charcoal) are used in self (or locally) made traditional mud (or metal) stoves. Moreover, we expect that the emissions from this stage do not contribute significantly in the overall life cycle of the fuels.

3 Life cycle inventory

Based on the system boundary in Fig. 1a, b, we prepared a detailed life cycle inventory for all cooking fuels. Table 1 gives the typical elemental composition, i.e., moisture, carbon,

nitrogen, oxygen, hydrogen, sulfur, and ash content of various fuels used in this study. The theoretical lower heating value (calculations given in the Electronic supplementary material 1) of firewood, crop residues, dung cake, and charcoal are taken as the embodied energy content, i.e., net calorific value (NCV). The NCV for coal, LPG, and kerosene is taken from various national fuel data standards. We took the cook stove efficiency from the literature (Smith et al. 2000; Venkataraman and Rao 2001).

3.1 Biomass fuels

Many tree species are used as cooking fuel of which the most common varieties used in India are acacia, eucalyptus, babool, sheesham, mango, etc. In this study, only manually collected firewood from local areas are considered as this is the usual practice in India. Thus, no additional resource inputs were taken. According to an estimate, around 234 million tons (MT) of firewood are annually consumed by households for cooking activities of which around 56 MT of firewood can be sustainably supplied by Indian forests without causing deforestation or degradation (refer to the Electronic supplementary material 1 for calculations). Therefore, 76 % of the firewood consumed in India for cooking activities were assumed to be supplied to by non-renewable sources outside forests (MoEF 2011) and is a leading cause of deforestation (Karanth et al. 2006; Nagothu 2001). Many crop residues such as rice, wheat, cotton, maize, millet, sugarcane, jute, rapeseed, mustard, groundnut, etc. are usually burned by households, and they are characterized by low bulk density and low energy yield per weight basis. The dung of stall fed cattle and buffaloes are converted in dung cake mainly by the women by mixing the collected dung with the residual feed (for example straw,
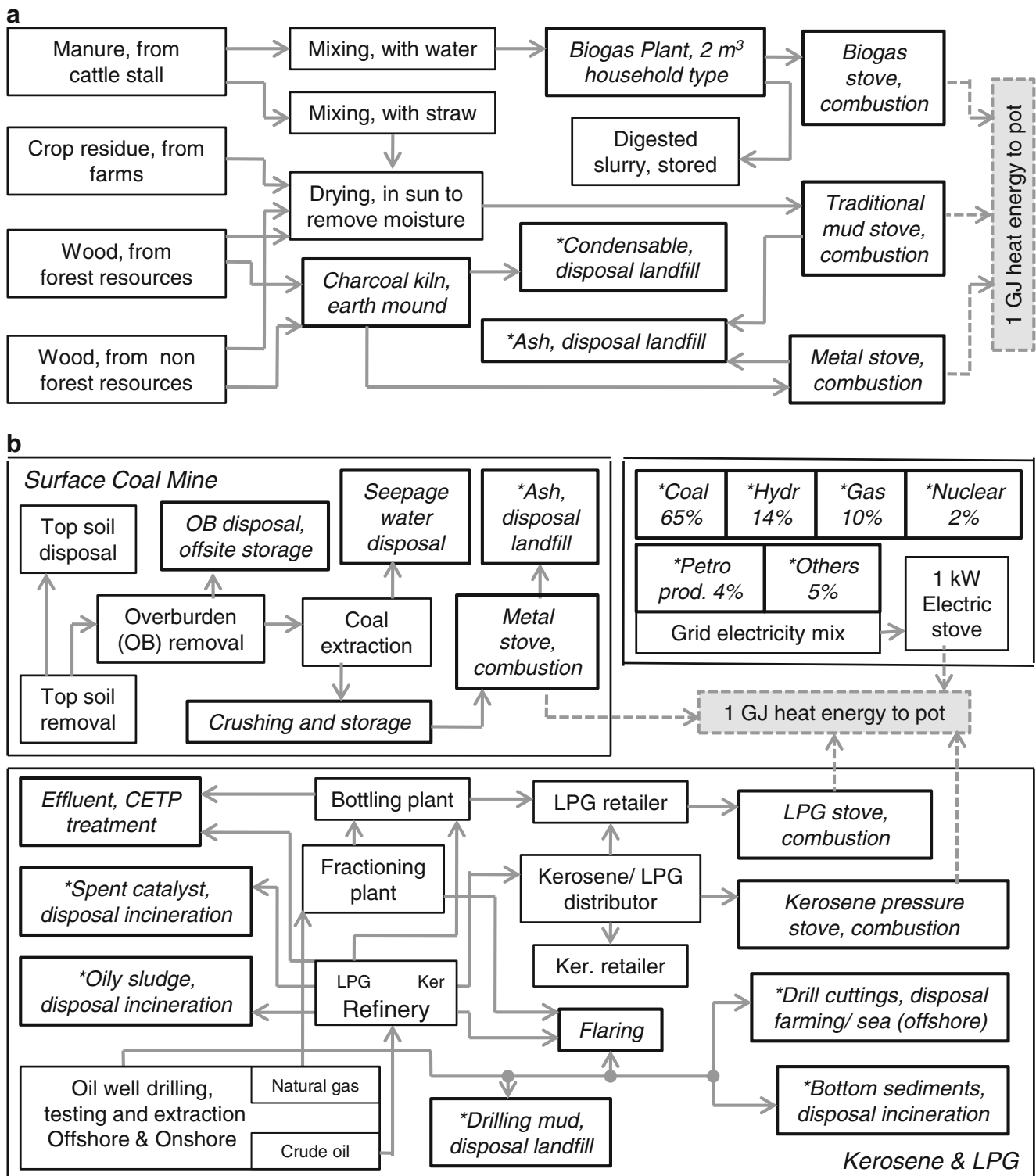
Fig. 1 **a** LCA system boundary of biomass fuels (emissions from processes marked with *asterisk* are from ecoinvent database) **b** LCA system boundary of fossil fuels (emissions from processes marked with *asterisk* are from ecoinvent database)

wood chips) and drying in the sun. The main emissions results from the combustion of fuel in the cook stove and some residual emissions results from the leaching of micro-nutrients to the soil from waste disposal of ash in landfills.

We reduced the ash quantity generated from the dung cake by a factor of 10 to correct for the concentration of heavy metals present in wood ash, which is about ten times higher than cattle dung (Itten et al. 2011). The estimated life cycle inventory is

presented in Table 2 (calculations and detailed inventory are given in the Electronic supplementary material 1).

3.2 Charcoal

Some of the collected wood is used for charcoal, which is produced by heating wood (or any other biomass) in a kiln (earth mound kilns are commonly used in India) with limited access to air through a process called "carbonization." Carbonization creates a fuel of higher quality than firewood. The charcoal yield from the kiln is approximated to be 30 %, and the "condensable" (a waste produced in the kiln during carbonization process) were assumed to be disposed in landfill or waste land. The emissions during the production process from the charcoal kiln and combustion emissions during cooking were taken from literature (refer footnotes "b" and "c" in Table 2). The left over charcoal ash from cook stove is disposed in landfills. Table 2 gives the estimated life cycle inventory of charcoal production and combustion (Electronic supplementary material 2 gives the additional information and detailed inventory).

3.3 Biogas

The fresh dung from cattle shed can also be used for biogas production as illustrated in Fig. 1a. The biogas system is based on 2 m^3 household type, fixed dome, anaerobic digester (AD) operating in continuous feeding mode for 350 days/year operating cycle and 10 years of operational life (Bagepalli CDM Project 2007). The AD is loaded with about 19.3 kg/day of fresh dung (mixed with a small quantity of water), which produces 1.31 m^3/day of biogas. The laboratory scale biogas models are used to compute the composition and mass balance

during pre- and post-anaerobic digestion process (Vivekanandan and Kamraj 2011). The leakage from the anaerobic digester is the sole contributor of the production stage emissions and is assumed to be 1 % of the total biogas generated (Afrane and Ntiamoah 2011; Borjesson and Berglund 2006). The digested slurry, a useful co-product, is removed from the digester and stored separately for applications in land farming and has been excluded from the biogas system boundary for impact analysis. The combustion stage emissions are estimated based on literature (refer to footnote "d" in Table 2). Table 2 gives the estimated inventory of biogas production and combustion (Electronic supplementary material 3 shows the calculations and detailed inventory).

3.4 Electricity and coal

"Ecoinvent unit process" is used to model the grid electricity generation (Fig. 1b using the dataset given by Itten et al. 2012, which is based on the Indian production mix in 2008. Table 3 presents the emissions from the life cycle inventory of electricity production.

The coal production scenario given in Fig. 1b is modeled for open cast mine (surface mine), which contributes over 80 % of the total coal production in India. Coal extracted in India is categorized into various grades A to G depending on the calorific content of coal. According to some experts from Coal India Ltd., only coal grades E to G are used for cooking purposes, which are almost, entirely supplied by open cast mines. The material and process flow are based on the average daily production data reported by Ghose (2004, 2007). Emission factors recommended by Central Institute of Mining and Fuel Research, India was used to calculate the fugitive methane emissions during surface coal mining and post mining handling. We estimated the total

Table 2 Life cycle inventory for firewood, crop residue, dung cake, charcoal, and biogas (in kilograms per gigajoules)

Description	Fire wood[a]	Crop residue[a]	Dung cake[a]	Charcoal		Biogas	
				Prod.[b]	Comb.[c]	Prod.	Comb.[d]
Carbon dioxide	721.00	922.00	1034.50	261	543.00	0.57	145.00
Carbon monoxide	36.64	46.44	39.46	57.34	57.34	x	0.19
Methane	2.23	4.81	5.64	6.25	1.65	0.36	0.043
Nitrogen oxides (NO_x)	0.41	0.76	0.76	0.008	0.24	x	0.038
Nitrous oxide	0.047	0.035	0.18	0.010	0.016	x	0.0009
NMVOC	3.90	5.81	16.02	18.76	2.15	x	0.056
Particulate matter	4.60	11.09	23.40	2.61	0.63	x	0.18
Sulfur dioxide	0.17	0.19	0.32	x	0.07	x	0.085
Ash*/cond. ±/AD slurry**	16.04*	19.12*	389.66*	12.93±	15.43*	106.0**	x

Note: Post combustion cookstove waste: Firewood, crop residue and dung cake (*)=ash; charcoal (±)=condesibles; biogas (**)=anaerobically digested slurry

[a] Smith et al. (2000), Venkataraman and Rao (2001), Reddy and Venkataraman (2002a), Saud et al. (2012), etc.

[b] Smith et al. (1999), Pennise et al. (2001), Adam (2009)

[c] Bhattacharya et al. (2000), Smith et al. (2000), Kadian et al. (2007)

[d] Smith et al. (2000), Borjesson and Berglund (2006), Kadian et al. (2007)

Table 3 Life cycle inventory for coal, electricity, and kerosene (in kilograms per gigajoules)

Description	Coal		Electricity generation[b]	Kerosene			
	Prod.	Comb.[a]		Extract.	Refinery	SHTD	Comb.[c]
Carbon dioxide	1.20	855.27	374.37	2.85	8.77	5.24	146.09
Carbon monoxide	0.39	26.88	0.062	0.007	2.31	0.45	3.08
Methane	0.52	2.57	2.39	0.091	0.040	0.012	0.036
Nitrogen oxides (NO_x)	0.11	0.55	1.31	0.018	0.033	0.061	0.05
NMVOC	0.001	5.76	0.025	0.002	1.2E−03	0.041	0.66
Particulates matter	1.62	17.22	0.61	0.003	0.043	x	0.15
Sulfur dioxide	0.01	1.46	2.87	0.004	0.093	0.007	0.127
Chemical oxygen demand	8.2E−03	x	x	1.2E−03	8.1E−04	x	x
Fluorine*/phenols[±]	6.3E−04*	x	x	1.5E−05[±]	2.0E−06[±]	x	x
Ash*/OB[±]/drill cuttings[**]	4,931.91[±]	219.44*	x	0.62**	x	x	x
Drill. mud*/spent catalyst[±]	x	x	x	0.07*	0.003[±]	x	x
BSW*/oily sludge[±]	x	x	x	9.0E−05*	0.008[±]	x	x

Note: Post combustion cookstove waste: Firewood, crop residue and dung cake (*)=ash; charcoal (±)=condesibles; biogas (**)=anaerobically digested slurry
BSW bottom sediment waste

[a] Reddy and Venkataraman (2002b), Chen et al. (2006), Zhi et al. (2008)

[b] Itten et al. (2012) (taken from final inventory list of SimaPro)

[c] Smith et al. (2000), Reddy and Venkataraman (2002a, b), Chen et al. (2007), Kadian et al. (2007)

emissions for all main production processes—topsoil removal, overburden (OB) removal (drilling, blasting, loading, and unloading), coal extraction (drilling, blasting, loading, and unloading), size reduction (crushing, conveyor belt loading, and bunker unloading), fugitive methane emissions (mining and post mine handling), and construction equipment/vehicular emissions. The OB is acidic in nature and unsuitable for farming (Rai et al. 2011) and, therefore, disposed in offsite wasteland. The combustion emissions during cooking are based on literature (refer footnote "a" in Table 3). The coal ash remaining after combustion is disposed in landfills (similar to biomass fuels). The estimated life cycle inventory of coal production and combustion is illustrated in Table 3 (calculations and detailed inventory are given in the Electronic supplementary material 4).

3.5 Kerosene and LPG

The kerosene and LPG production scenarios are modeled based on the raw material, crude oil, and natural gas, extracted in India (illustrated in Fig. 1b), although the bulk of the share is imported from various countries. As the main focus is the Indian scenario, we investigated the domestic production chain of crude oil (and natural gas) only. We do not expect the error resulting from excluding overseas production chain to impact the findings significantly because (a) the production chain from refinery stage onwards remains the same and (b) the Indian companies engaged in extraction of crude oil and natural gas follow operational standards founded on globally accepted principles and practices, almost identical to the

overseas oil companies. The "extraction stage" of crude oil and natural gas is based on the drilling, metering, testing, and servicing of oil wells and production data of Oil and Natural Gas Corporation (ONGC is the largest oil company in India operating upstream) for 2010–2011. To calculate the extraction stage emissions inventory, we used default emission factors from standard literature for drilling, testing and servicing operations, fugitive emissions, equipments and machinery, flaring units, grid electricity, etc. The drill cuttings from offshore sites are disposed in the sea and those from onshore sites in waste/farm lands. The hazardous waste incineration is used to dispose the bottom sediment waste containing oily sludge and toxic substances.

The extracted crude oil sent to refineries undergoes several complex processes before final conversion to multiple petroleum products. The production data for the period 2010–2011 of Indian Oil Corporation, a leading public sector unit with 8 refinery complexes and combined crude oil throughput of 53 MMT, is used to model the "refinery stage" emissions. We used the recommended default emission factors used by various standards (e.g., Intergovernmental Panel on Climate Change (IPCC), Environmental Protection Agency (EPA) AP42, Central Pollution Control Board (CPCB), etc.) to estimate the emissions from fluid catalytic cracking unit, vapor recovery system and vacuum distillation column condenser, fuel oil and gas boilers, and waste water discharge. Refinery processes are highly energy intensive and produce palette of multiple products with different energy contents, and it is possible to allocate the emissions to the specific products using various schemes. In this study, a simple scheme based on the oil equivalent conversion factor, i.e., ratio

of lower heating value (LHV) of the end product to that of crude oil has been used to compute the production share of LPG and kerosene in the petroleum product palette. The refinery emissions are allocated based on this production share. The disposal method used for spent catalyst and oily sludge is by hazardous waste incineration.

The extracted natural gas is sent to the gas fractioning plants, and the system boundary is modeled based on the 2010–2011 production scenario of LPG production line of ONGC Uran Gas fractioning plant located near Mumbai, India. The emissions from gas sweetening plants and reciprocating compressor engines have been calculated based on the default emission factors from EPA AP 42 Guidance document, and those from flaring units, grid electricity, etc. are calculated using emission factors used earlier for extraction stage. The emissions have been allocated using similar schemes as in refineries. There are no significant wastes generated at the plant as the major share of the discharged effluents is reused after treatment.

The LPG produced in refineries and fractioning plants are sent to the bottling plants where they are filled in steel cylinders, which are then supplied to households by distributor/retailer network spread over the entire country. The bottling stage is simulated based on the per-day production scenario of IOCL Barkhola bottling plant located in Assam, India. This is one of the recent state-of-art bottling plant commissioned by IOCL and is considered to be a representative of bottling plants in India for this study. The main emissions are non-methane volatile organic compounds (NMVOC) resulting from LPG leakages during transfer and filling operations, use of grid electricity, and waste water discharge, which have been computed based on emission factors recommended by CPCB and literature (Jungbluth 1996).

The storage, handling, transportation, and distribution (SHTD) of LPG and kerosene is modeled based on assumptions on route and mode of transport (sea, rail, or road), average distances covered, nature of trip (one or two way), typical travel time, etc. The assumptions have been made to represent the broad Indian scenario. The cooking stage emissions for kerosene and LPG are taken from literature (refer to footnote "c" in Table 3 and "a" in Table 4). The stage wise life cycle inventory for kerosene is presented in Table 3 and for LPG is illustrated in Table 4 (calculations and detailed inventory are given in the Electronic supplementary material 5).

3.6 Impact assessment

In this study, ReCiPe 2008 midpoint life cycle impact assessment (LCIA) method based on hierarchist perspective has been used. ReCiPe is an LCIA method that is harmonized in terms of modeling principles and choices, offering results at both the midpoint and endpoint level. The midpoint approach is based on baseline methods for characterization similar to those of "CML 2002" and is considered to have relatively lower uncertainty, higher acceptance and closer to IPCC with regards to the global scenario (Goedkoop et al. 2009). ReCiPe is considered as the successor of "problem-oriented approach" of CML 2000 LCIA methodology and "damage-oriented approach" of "Ecoindicator 99." Although ReCiPe methodologies are modeled for European temperate and sub-tropical climates, there is no specific limitation on its application to other climatic conditions. Furthermore the life cycle impact method is used to inter compare various fuel systems on a generic basis; therefore, the inherent design incompatibility of the ReCiPe with the

Table 4 Life cycle inventory for LPG derived from crude oil and natural gas (in kilograms per gigajoules)

Description	LPG (crude oil)			LPG (natural gas)			Bottling plant	Comb.[a]
	Extract.	Refinery	SHTD	Extract.	Fract.	SHTD		
Carbon dioxide	2.42	7.40	9.75	2.30	1.61	8.39	0.90	119.70
Carbon monoxide	0.006	1.96	0.097	0.005	6.9E−04	0.089	1.5E−04	0.58
Methane	0.077	0.034	0.01	0.074	0.066	0.053	0.005	0.003
Nitrogen oxide	0.015	0.027	0.12	0.014	0.011	0.1	0.003	0.06
NMVOC	0.001	1.0E−03	0.046	0.001	0.002	0.019	0.001	0.41
Particulate matter	0.002	0.038	x	0.002	0.004	x	0.001	0.03
Sulfur dioxide	0.003	0.08	0.006	0.003	0.17	0.001	0.007	0.082
Phenols	1.3E−05	1.9E−06	x	1.3E−05	x	x	9.7E−06	x
Oil and grease	3.5E−04	2.7E−05	x	3.0E−04	x	x	3.8E−05	x
Drilling cuttings	0.53	x	x	0.47	x	x	x	x
Drill. mud*/spent catalyst±	0.06*	0.002±	x	0.055*	x	x	x	x
BSW*/oily sludge±	7.8E−05*	0.006±	x	x	x	x	x	x

Note: Post combustion cookstove waste: Firewood, crop residue and dung cake (*)=ash; charcoal (±)=condesibles; biogas (**)=anaerobically digested slurry

BSW bottom sediment waste

[a] Smith et al. (2000), Reddy and Venkataraman (2002b), Chen et al. (2007), Kadian et al. (2007)

tropical climatic conditions of India is not expected to impact the findings of this study significantly. ReCiPe 2008 comprises of two sets of impact categories with associated sets of characterization factors. At the midpoint level, 18 impact categories are addressed. At the endpoint level, most of these midpoint impact categories are further converted and aggregated into the following three endpoint categories, i.e., human health, ecosystems, and resource surplus costs. Thirteen impact categories at midpoint level have been selected for evaluation of cooking fuel performance in this study.

4 Results and discussion

Figure 2 presents the study results of LCIA. For better visualization, the relative contribution of all the cooking fuels towards each ReCiPe impact category is presented as a percent share of the maximum contributor.

4.1 Coal and electricity

The contribution of coal is 978 kg CO_2eq per GJ to climate change (Fig. 2a) and 0.57 kg dicholorobenzene (DCB) per GJ

Fig. 2 Life cycle environmental impacts of analyzed cooking fuels

to freshwater ecotoxicity (Fig. 2c), which is highest among the assessed cooking fuels. Also, use of coal for cooking activities contributes significantly to particulate formation, acidification, and marine ecotoxicity. Figure 3a illustrates the percent distribution of environmental impacts in production and combustion of coal, and it is evident that the combustion stage contributes over 95 % of the total impacts to climate change, photochemical oxidation, particulate formation, and acidification. The mining of coal contributes significantly to eutrophication (freshwater and marine) and other toxicological impacts such as human toxicity, terrestrial, fresh water, and marine ecotoxicity.

All environmental impacts for electricity results from the production stage as it does not involve any chemical combustion in the cook stove. As can be seen from Fig. 2, electricity contributes the most to terrestrial acidification (3.61 kg SO_2eq), ozone depletion (11.1E−06 kg CFC-11 eq), eutrophication (freshwater=9.37E−03 kg Peq and marine=0.0531 kg Neq), human toxicity (39.6 kg DCB), and marine ecotoxicity (0.311 kg DCB). Also, the contribution of electricity is the highest among studied fuels for metal (0.168 kg Fe eq) and fossil depletion (97.5 kg Oileq) impact categories. The dominant use of coal for its production contributes significantly towards its global warming potential (GWP).

4.2 Kerosene and LPG

Kerosene contributes the most for terrestrial ecotoxicity (0.044 kg DCB) closely followed by LPG and electricity (Fig. 2c). Figure 3b presents the stage wise distribution of environmental impacts for kerosene. The combustion of kerosene in the cook stove significantly contributes to the atmospheric impacts, namely climate change (85 %), photochemical oxidation (73 %), PM formation (74 %), and acidification (41 %). Refineries contribute the maximum to the production stage atmospheric impacts, particularly climate change (45 %), ozone depletion (79 %), PM formation (62 %), acidification (72 %), and photochemical oxidation (56 %). The extraction of crude oil contributes significantly to freshwater eutrophication (90 %) and toxicity impacts such as human toxicity (89 %), terrestrial (99 %), marine (51 %), and fresh water ecotoxicity (37 %). As seen from Fig. 3c, the distribution pattern of impacts for production stages of LPG derived from crude oil is somewhat similar to that of kerosene, except that the SHTD stage environmental impacts are more dominant. The combustion stage contribute significantly to climate change (82~87 %), photochemical oxidation (58~73 %), and PM formation (35~37 %). The contribution of bottling stage is less than 1 % to most impact categories. From Figs. 2 and 3e, it can be seen that LPG (NG) perform slightly better than LPG (CO), primarily because the fractioning plants contribution to environmental impacts such as climate change, human toxicity, photochemical oxidation, fresh water, and marine
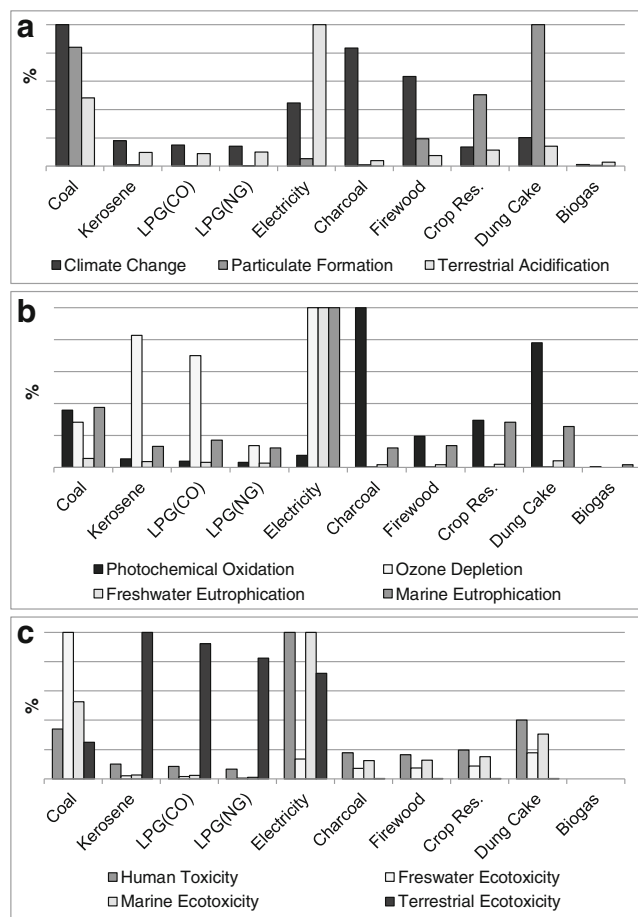
Fig. 3 **a** Distribution of environmental impacts of coal use; **b** distribution of impacts of kerosene use; **c** distribution of environmental impacts from use of LPG (CO); **d** comparison of selected environmental impacts from SHTD of kerosene, LPG (CO), and LPG (NG); **e** distribution of environmental impacts from use of LPG (NG); and **f** distribution of environmental impacts of charcoal use (*Prod.* production stage, *Comb.* combustion stage, *Extr.* extraction stage, *Refn.* refinery stage, *Fract.* natural gas fractioning stage, *Botl.* bottling stage; and *SHTD* storage, handling, transportation, and distribution stage)
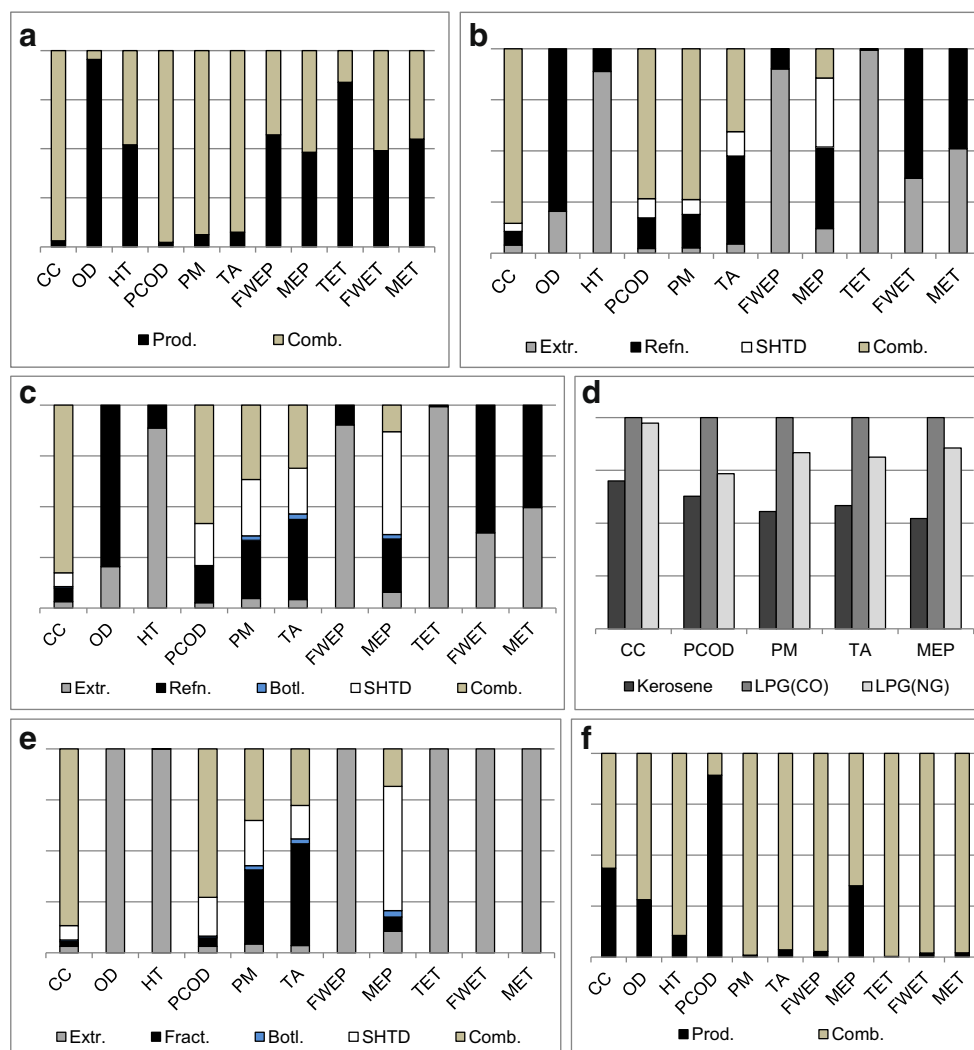
ecotoxicity are significantly lower than those of refineries. However, the emissions of particulates and SO_2 (Fig. 2a) by fractioning plants tend to be marginally higher than refineries due to gas leakages during processes from valves, compressors, gas flaring, etc. The performance of LPG (NG) is significantly better than LPG (CO) for ozone depletion, human toxicity, and ecotoxicity (fresh water, marine, and terrestrial) impact categories (Fig. 3c, e).

Kerosene is only marginally inferior to LPG with 15~18 % higher impacts on most impact categories, but being a liquid fuel has a distinct advantage in SHTD stage (Fig. 3d), where the impacts are seen to be 30~40 % lower than that of LPG. Kerosene can be potentially better cooking fuel option for rural areas for the following reasons: (1) Lower population densities are spread over vast distances compared to urban areas. (2) LPG is typically supplied in 14.2 or 5 kg cylinder which requires a substantial investment at the time of purchase of fuel, whereas kerosene is sold on the pro-rata basis in any unit quantity desired by the consumer. The rural population in India largely comprises of daily wage agricultural workers

who would find it difficult to buy LPG in higher quantities at once. (3) The unpaved or semi-paved roads make it difficult to transport LPG steel cylinders in stacks possibly damaging the containers. (4) The responsibility of cooking including procurement of fuel is mostly the responsibility of women in rural areas, hence carrying an empty LPG cylinder to the shop and transporting filled cylinder back is highly taxing as the weight of the LPG cylinders ranges from 13 to 27 kg.

From Fig. 3d, the impacts from the SHTD stages of LPG (NG) are seen to be slightly lower than LPG (CO), which is primarily due to the transportation of natural gas to the fractioning plants from offshore and onshore extraction sites using gas pipelines. Overall, the environmental performance of LPG produced from natural gas is relatively much better than crude oil derived LPG. The main reason is that the refineries are more energy intensive compared to fractioning plants and generate substantial quantities of toxic wastes, namely bottom sediment oily sludge, spent catalysts, effluents, etc., which require comprehensive waste management programs. Also, natural gas is easier to transport using

pipelines from extraction points located in offshore and on-shore locations to fractioning plants, which can substantially reduce the emissions due to evaporative losses during storage, handling, and transmission.

4.3 Biomass fuels

The characterization factor of particulate matter formation is the intake fraction of PM_{10}, which also gives a quantitative measure of indoor/outdoor air pollution during cooking activities. Dung cake (21.4 kg PM_{10}eq) contributes highest to this impact category (Fig. 2a). The indoor air pollution potential of dung cake is twice that of crop residue and about five times higher than firewood. The black carbon emissions are 1.3 and 1.5 times higher than that of crop residues and firewood, respectively. Dung cake contributes 18~20 % higher than coal for human toxicity and indoor air pollution impact categories. The GWP of renewable biomass fuels (crop residue and dung cake) is high due to atmospheric release of methane and nitrous oxide during its combustion in the cook stoves and is broadly comparable to that of petroleum-based fuels (Fig. 2a). From LCIA results (Fig. 2), it is quite clear that dung cake followed by crop residues are the worst performers among biomass cooking fuels despite being fully renewable resources. The large-scale use in rural areas can solely be attributed to its economic attractiveness in being freely and abundantly available locally.

Firewood is the most widely used biomass cooking fuel in India. More than 75 % of the wood used in cooking activities comes from non-renewable sources, which means that CO_2 emissions resulting from firewood combustion (non-renewable share) will remain in the atmosphere and need to be accounted in climate change impact assessment. The CO_2 emissions from combustion of renewable share can be discounted as biogenic CO_2 will be absorbed by the biomass during its growth cycle. Due to the impact of deforestation on climate change, the use of firewood in cooking activities contributes significantly to this impact category after coal and charcoal. However, in the scenario that the entire firewood is supplied from renewable sources, the GWP will sharply reduce to 71 kg CO_2eq per GJ (reduction of 88 %). Therefore, the actual resources from which the firewood will be used for cooking activities will have a considerable bearing on its contribution towards climate change. The environmental performance of firewood is 20~30 % better than crop residues and two to approximately five times better than dung cakes on other impact categories (Fig. 2).

4.4 Charcoal

The contribution of charcoal is highest (21 kg NMVOC) for photochemical oxidant formation (generally referred as summer smog), followed by dung cake (16.4 kg NMVOC), coal,

crop residue, and firewood (Fig. 2b). The main reason is the release of high amounts of carbon monoxide to the environment from charcoal kilns (Fig. 3f). It can be seen from Fig. 3f that the production of charcoal contributes significantly to photochemical oxidation (89 %), climate change (44 %), marine eutrophication (35 %), and ozone depletion (28 %) impact categories. The performance of charcoal (0.213 kg PM_{10}eq) is comparable to that of kerosene (0.205 kg PM_{10}eq) for PM formation impact category, i.e., indoor/outdoor air pollution (Fig. 2a). The acidification potential of charcoal is about 50 % lower than that of firewood (Fig. 2a).

The impact of renewable/non-renewable allocation of wood source (discussed in the earlier section) is also observed in the GWP of charcoal. If charcoal is made from wood supplied from renewable sources, the GWP will reduce by about 75 %. It can be seen that in such a scenario, except photochemical oxidation, the environmental performance of charcoal can broadly be compared to that of kerosene for most the impact categories. The LCIA results indicate that charcoal produced from renewable biomass such as coconut shells and bamboo waste will deliver remarkably better environmental performance than traditional biomass fuels. The other advantage of converting the woody biomass to charcoal is reduction in the unit energy cost of transportation due to significant weight reduction and its suitability for long-term storage. On the other hand, there is a net loss of energy in charcoal production (low yield of 30 %), although part of energy is recovered during combustion due to better heat transfer efficiency of charcoal stoves (Table 1). Overall, the woody biomass to charcoal conversion efficiency is the key issue determining the practical usefulness of charcoal as cooking fuel and also for achieving high mitigation effects (Steubing et al. 2012).

4.5 Biogas

It is readily evident from LCIA results presented in Fig. 2 that biogas contributes the lowest to all impact categories except particulate formation (0.154 kg PM_{10}eq), where it is marginally higher than LPG (0.10 kg PM_{10}eq). Biogas contributes about 10.5 kg CO_2eq per GJ to climate change impact category, out of which over 90 % is due to methane gas directly leaked to the environment from AD during biogas production. All other environmental impacts come from the combustion of biogas in the cook stove. The environmental performance of the biogas for cooking activities from small household digesters is comparable (or even exceeds for some impact categories like HT, FWEP, OD, PCOD, etc.) to that of LPG while also converting the cattle manure into a useful co-product, i.e., digested slurry. The greenhouse gas (GHG) mitigation potential of biogas systems are excellent only when waste material is used as substrate for biogas production as seen from this study. GWP of biogas is 14 times lower than those of dung cake even

though both use same cattle manure as raw material. However, some caution is required in interpreting the LCIA results presented in this paper for biogas. The impacts arising from using the digested slurry in farming application have not been included in the LCA. Although some experts advocate that the digested slurry has a better fertilizer value as compared to dung cake ash or fresh manure, no reliable studies could be found which could conclusively demonstrate the superiority of the digested slurry over dung cake ash or fresh manure in quantitative terms. Also, methane (which has 21 times higher GWP than CO_2) is directly leaked to the environment from digesters during biogas production. The climate change impacts are directly correlated to leakage amounts, which may be significantly higher than 1 % for household biogas systems due to the frequent charging required for household anaerobic digesters. In any case, there is no ambiguity that the performance of the biogas system would still be better than other fuel options despite considering the higher leakages and digested slurry farming use impacts. The suitability of the biogas system for cooking activities has been advocated by numerous studies (e.g., Banerjee and Tierney 2011; Kurchania et al. 2011; Ravindranath and Balachandra 2009). According to Rao et al. (2010), the installed capacity of waste to energy biogas system is about 1,227 megawatts (MW), which is merely 4.8 % against a total estimated potential of 25,700 MW in India.
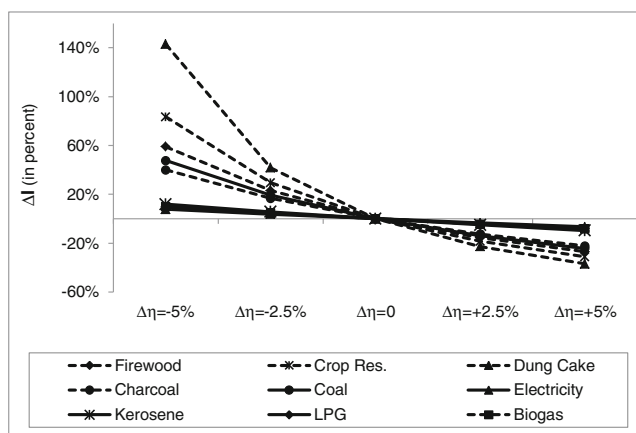
4.6 Impact of stove efficiency

The correlation between percent change in stove efficiency ($\Delta\eta$) and percent change in environmental impacts (ΔI) are illustrated as sensitivity analysis in Fig. 4, where I represents any selected life cycle impact categories used in this study for environmental impact assessment of cooking fuels. A cook stove's performance can be characterized by (1) combustion efficiency, i.e., energy stored in the fuel converted to heat is a function of fuel type, combustion stages, etc., and (2) heat

Fig. 4 Influence of change in stove efficiency on life cycle environmental impacts of cooking fuels

transfer efficiency, i.e., heat absorbed by the cooking pot which is largely influenced by stove design. In India, many agencies (governmental and private) are actively involved in improving stove designs (particularly biomass stoves) to improve its heat transfer efficiencies. Improvement in stove efficiencies is bound to lower the atmospheric emissions during cooking activities. It can be seen from Fig. 4 that life cycle environmental impacts "ΔI" of traditional fuels (such as dung cake, crop residues, and firewood), coal, and charcoal exhibit high sensitivity (characterized by hyperbolic progression) towards any change in stove efficiency ($\Delta\eta$). The main reason can be attributed to the sharp increase in required fuel quantity to produce the 1 GJ of useful heat energy inside the cooking pot as the heat transfer efficiencies of traditional fuels are much lower than those of commercial fuels (refer last column of Table 1). For example, a 5 % decrease in the heat transfer efficiency of dung cake stove results in nearly 2.5 times increase in dung cake quantity (i.e., from 988 to 2,400 kg), which sharply increases the environmental impacts (ΔI) by 143 %. The correlations between electricity, kerosene, LPG, and biogas life cycle impacts with the stove efficiency are found to be robust (characterized by almost linear progression) because of much better heat transfer efficiencies of the cook stoves (refer Table 1). Overall, it can be said that life cycle impacts reduce significantly with the improvement in stove efficiencies.
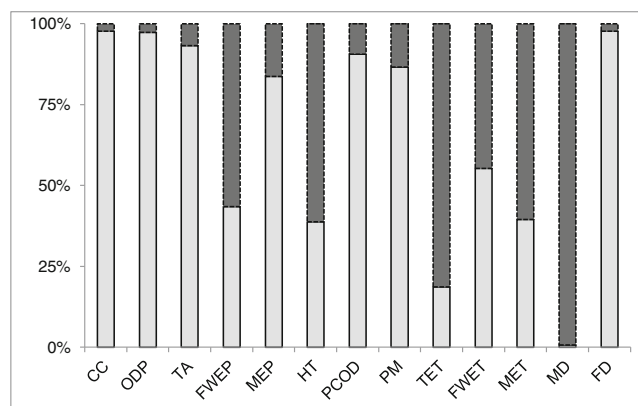
4.7 Impact of infrastructure

The role of infrastructure has a considerable bearing on the environmental pressures and cannot be discounted from any life cycle impact analysis, though the data consistency required for a proper LCA is seldom available in the public domain. In this study, from Fig. 1b it is evident that commercial fuels such as LPG, kerosene, and electricity require enormous investments in infrastructure for extraction, processing, and distribution before it can be used for cooking activities. Whereas, biomass fuels (Fig. 1a) like firewood and crop residues are almost freely available and can be used directly as cooking fuels after drying to remove excess moisture. Biogas plants and charcoal kilns require some level of infrastructural investment, although negligible compared to fossil fuels, for producing cooking grade fuels. Much of the infrastructures required for mining coal from open cast mines are usually shifted from one location to another.

To gain an insight to the impact of infrastructure on the LCIA results, unit process from ecoinvent database for petroleum based fuels (LPG and kerosene) and electricity has been analyzed (calculations and details are given in the Electronic supplementary material 6). The results for petroleum-based cooking fuel (LPG and kerosene) in terms of percent share of impacts due to infrastructure are presented in Fig. 5. It can be

Fig. 5 Estimated increase in life cycle environmental impacts of LPG and kerosene due to inclusion of infrastructure (*highlighted in darker shade*)

seen that inclusion of infrastructure leads to significant increase in (1) metal depletion (99 %) due to the extraction of iron, manganese, nickel, copper, etc. for production of infrastructure; (2) terrestrial ecotoxicity (81 %) due to phosphorous emissions into the soil from disposal of drilling waste from creation of oil wells; (3) human toxicity (61 %), marine (61 %), and fresh water (45 %) ecotoxicity due to heavy metal emissions such as manganese, zinc, and nickel into the water from disposal of tailings from copper beneficiation for the copper used in the infrastructure; and (4) freshwater eutrophication (57 %) due to phosphate emissions from mining of lignite and coal used for generation of electricity in infrastructure and disposal of tailings from copper beneficiation. For electricity, the share of metal depletion impacts from infrastructure is almost 100 %, largely due to extraction of copper mainly used in the distribution network and other metals such as iron, manganese, and nickel used in production of infrastructure.

5 Conclusions

The study assessed the life cycle environmental footprint of all the cooking fuels used in India. The study concluded that among the compared alternatives, certain fuels have a much better environmental performance than others. The Indian household cooking predominantly revolves around LPG and firewood. While the former is heavily subsidized, the later is largely collected for free from the forests and various other sources. In areas where fewer opportunities exist to collect firewood, they are readily substituted with crop residues and dung cake. The real challenge to the policy makers is to regulate and/or discourage the use of traditional fuels for cooking purposes and to facilitate the households to switchover to other environmentally better performing fuel options. This challenge can be addressed to some extent by (a) offering more cooking fuel options to households such as

biogas and charcoal, and (b) addressing the economic attractiveness of traditional fuels (particularly crop residues and dung cake), which are freely available and locally abundant.

In this study, we empirically demonstrated that the environmental impacts of biogas are lower than that of LPG. Moreover, it is processed from locally available organic wastes and is totally renewable. Promotion of biogas on a large scale offers immense potential for GHG mitigation and can also provide additional co-benefits such as substituting chemical fertilizers, local skill development, and employment generation. Charcoal is another cooking fuel option with better environmental performance, especially charcoal made from renewable woody biomass which can broadly match the environmental performance of kerosene. Charcoal production also provides additional co-benefits like local employment generation and skill development, entrepreneurship, and export possibilities. The other key advantage associated with biogas and charcoal is that, on a large scale, they provide ample opportunities for bulk utilization of organic wastes (i.e., crop residues and animal dung) and thus significantly reduce the quantity available for direct combustion in cook stoves. Also, the use of kerosene in cooking activities has been declining in the recent years but is found to be more environmental friendly than LPG for transportation and distribution. Furthermore, sustainably grown firewood can be a potential source of bio-energy for cooking activities, particularly in processed form. The improvement in biomass stove efficiency can play a significant role in achieving high mitigation effects. Finally, in view of the prevailing cooking fuel use scenario in India, kerosene, biogas, and charcoal seem to be an environmentally suitable fuel options for rural areas, and LPG, kerosene, and biogas are suited for urban areas for meeting the cooking energy demands of the households. However, the generic life cycle assessment of various fuels in this study is insufficient to draw final conclusions on this hypothesis and more research is required especially on "socio-economic" and "policy" perspective of the suggested rural–urban fuel mix. Further, there is a need to analyze other options such as solar cooking, ethanol stoves, and biomass briquettes comprehensively to determine the most sustainable cooking option in India.

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